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THE JPL ROADMAP FOR DEEP SPACE NAVIGATION

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This paper reviews the tentative set of deep space missions that will be supported by NASA's Deep Space Mission System in the next twenty-five years, and extracts the driving set of navigation capabilities that these missions will require. There will be many challenges including the support of new mission navigation approaches such as formation flying and rendezvous in deep space, low-energy and low-thrust orbit transfers, precise landing and ascent vehicles, and autonomous navigation. Innovative strategies and approaches will be needed to develop and field advanced navigation capabilities.

INTRODUCTION

The NASA Deep Space Mission System (DSMS) comprises both the Deep Space Network (DSN) antennas, with the associated communication and control equipment, and the Advanced Multi-Mission Operations System (AMMOS). The AMMOS provides tools, products and services to help operate NASA's missions, including those required to design and navigate missions.

DSMS periodically compiles the set of future missions that it will be called to support for the next twenty-five years, in order to forecast which communications and navigation capabilities will be required by those missions. DSMS uses this mission set to study and plan the evolution of the DSN and the AMMOS, and prepares a roadmap for the next twenty-five years. The DSMS roadmap lists strategic goals mostly in relation to communication capabilities, but also includes the improvement of spacecraft tracking and navigation services to both enhance current capabilities and to enable new classes of future missions.

FUTURE MISSION SET, CHALLENGES AND REQUIRED CAPABILITIES

The set of future NASA deep-space missions changes periodically, as missions are added to or removed from the forecast. The set of missions in a five-year horizon is well known and fairly stable, but trying to forecast up to twenty-five years from now requires some educated guesswork. NASA produces a Strategic Plan, and a number of NASA panels and committees prepare roadmaps and surveys for different themes such as Solar System Exploration, Robotic and

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Human Exploration of Mars and others. From those sources DSMS compiles the set of missions[1] that most probably it will need to support, coordinating with other NASA mission modeling efforts, in order to ensure emergence of, and consistency with, a commonly agreed upon "snapshot" of potential mission customers over the next twenty-five years. Recently, such coordination has involved building a consensus view relative to the Space Communications Architecture Working Group's (SCAWG) Integrated Mission Set (IMS) and the Program Analysis & Evaluation (PA&E) Office's Advance Mission Planning Model (AMPM). Once the mission set is defined, the DSMS strategic planners then research mission requirements documents, review presentations, and concept studies to derive the communication and navigation needs for each mission[2]. For future competed opportunities, such as Mars Scouts, New Frontiers and Discovery, DSMS needs to make some educated guess of which are the most probable mission types. In addition DSMS needs to think about what would be the needs of other future missions that are not currently possible given the current DSMS infrastructure and capabilities. Competed missions are not likely to ask for new DSMS capabilities, because doing so may increase the cost and risk posture of the proposal, and therefore make it less likely to be selected. However, it would be foolish for NASA to always constrain itself to its current DSMS capabilities, because doing so would exclude many worthwhile projects, and asymptotically decrease the exploration and science return of new missions. Most of the high-return missions possible with current capabilities have been done already or are being done now. Table 1 lists some of the most challenging current and future missions that DSMS is supporting or may have to support.

Table 1
CURRENT AND FUTURE MISSION CHALLENGES

Mission	Characteristics and Challenges
Mars Reconnaissance Orbiter	*Ka-band downlink, optical navigation experiment, high precision navigation in orbit*
Dawn (minor planet orbiter)	*Low-thrust, optical navigation*
Phoenix (Mars polar lander)	*Unbalanced ACS thrusters, difficult communication geometry*
Mars Science Laboratory (rover)	*Requirement to be able to land at a high elevation, EDL with a heavier landing vehicle, hazard avoidance*
Juno (Jupiter polar orbiter)	*Ka-band tracking*
Mars Scout – landers/rovers	*Increased reliance on in-situ navigation means, pinpoint landing, hazard avoidance*
Mars com/nav relay orbiter	*UHF, X-, Ka-band and/or optical links*
Mars Sample Return	*Pinpoint landing, Mars ascent, Mars-orbit rendezvous*
Mars Scout – aero-rovers	*Atmospheric navigation at Mars*
Comet surface sampling mission	*Close-proximity operations in an unpredictable environment, flight path/attitude control interaction, pinpoint landing*
Outer-planet moon orbiter	*Three-body navigation, radiation environment, long round-trip light times*
Multiple-spacecraft telescopes	*Precision formation flying*
Venus in-situ explorers	*EDL and/or atmospheric navigation at Venus*
Mars human precursor missions	*Demonstration of highly reliable capabilities*
Outer-planet moon lander	*Three-body navigation and EDL, radiation environment*

The main trends and challenges that can be derived from these missions are:

1. Increased challenge from round-trip light time, either because operations are done further away from the Earth, or because the kind of things that can be done are limited if the ground has to be in the loop.
2. Increased use of in-situ and autonomous navigation: Mars in-situ relays, optical navigation, close-proximity operations.
3. Increased use of low-thrust propulsion and low-energy transfers using three- or four-body dynamics.
4. Increased need for higher accuracy in guidance, navigation, and control.
5. Increased need for integration between flight path and attitude control.

In addition there is always the desire to decrease the cost and risk of high-performance navigation, by producing low-weight, low-cost, highly reliable navigation components. The availability of these components will enable missions that would not be possible or affordable otherwise.

DSMS also performs the same kind of analysis for deep-space communication capabilities[3], and it is proposing improvements in the deep-space communications infrastructure that can also benefit navigation. Some of the trends in the communications side that can be leveraged by navigation users are:

1. Use of arrays of many smaller radio antennas.
2. Transition to higher frequency bands, in particular Ka-band and possibly optical.
3. Increased reliance on in-situ communication links.
4. Increased inter-operability with other science and space agencies.

ENABLING STRATEGIES

Many of the navigation capabilities required by future missions are currently available, but some new missions have requirements that cannot be fulfilled without improving existing capabilities or developing new technologies. The following are the strategies that DSMS plans to follow in order to improve deep-space navigation capabilities.

Advance Radio-Metric Tracking Capabilities

DSMS will leverage the improvements in communication capabilities in order to benefit its navigation users, including the migration to the Ka frequency band and the deployment of large arrays of smaller antennas.

Arrays of smaller antennas can benefit navigation in multiple ways. A large array can have more sensitivity than a single antenna, and allow for uninterrupted tracking during many mission-critical phases, including entry, descent and landing (EDL). The array size can be adjusted o fulfill the particular requirements of a mission for each of its mission phases, so fewer antennas can be used when the only requirement is for range and Doppler, and more when high-rate telemetry is also needed. If the number of antennas is high enough, it could be possible to have continuous Doppler-only tracking for many spacecraft, without tying up a bigger antenna, and also to have continuous tracking of radio-frequency sources for fast Earth orientation calibration. Smaller antennas have a wider beam, so multiple close spacecraft (e.g. all the spacecraft at or approaching Mars) and natural radio-frequency sources can be tracked simultaneously and new tracking techniques, such as Same-Beam Interferometry, can be used routinely. In addition weaker and therefore more numerous and closer quasar sources could be used with the increased sensitivity, increasing the Very Long Baseline Interferometry (VLBI) measurement accuracy. Antenna arrays can also be used to precisely determine the angular position of spacecraft near the Earth and are particularly useful for early orbit search and acquisition. The increased communication rates can be used to rapidly download higher volumes of more detailed optical navigation pictures and spacecraft small-force and attitude data.

Ka-band tracking has the advantage that it is less sensitive to charged-particle effects and has a smaller measurement noise. Moreover, radio-frequency sources are more compact in Ka-band. However, in order to be able to use Ka-band tracking at its full potential it will be necessary to improve the accuracy and timeliness of neutral media and Earth orientation calibrations, and to obtain a more precise quasar catalogue for Ka-band sources.

Sharing antenna assets with other science and space agencies will increase the availability of spacecraft VLBI tracking. Today, using only DSN assets, it is only possible to perform VLBI tracking of a given spacecraft twice a day in two somewhat narrow temporal windows when two DSN ground complexes have common visibility of the spacecraft. Using additional sites we could obtain improved observation geometry, when using distant antennas with the same approximate longitude, and have many additional tracking opportunities.

In the future the DSN should be able to perform pseudo-noise ranging, in order to increase ranging accuracy and reduce the impact of ranging on data rates; and it should improve the accuracy of range calibrations, by performing automated, multiple-frequency antenna delay calibrations. Increased DSN automation, required to efficiently and affordably operate large arrays of antennas, would also benefit navigation by allowing navigation users to reliably optimize the tracking parameters in order to accommodate changes in the communication link and the accuracy needs.

For the space segment we should pursue the development of light-weight multi-band digital transponders that can regenerate the range signal, and can use pseudo-noise range coding.

Expand the Use of Optical Navigation

Optical navigation (opnav) is the use of an onboard camera to image solar system bodies against a star background in order to improve the knowledge of the spacecraft's angular position relative to that body. The solar system body can be a planet, planetary satellites, or minor planets such as asteroids or comets. This data type can be used on its own, or as is more common, combined with radiometric data types to compute a navigation solution.

The data type is most useful when the ephemeris of the target body is not known to high accuracy. Thus, it has been extensively used for missions to the outer planets, either for flybys as for Voyager at Jupiter, Saturn, Uranus and Neptune, and Galileo and Cassini for satellite tours. For Voyager, opnav was used to image the large satellites in order to pinpoint the location of the spacecraft relative to the planet (a technique which can also be applied at Mars, as has been demonstrated by Viking and will be again for the Mars Reconnaissance Orbiter during its approach to Mars). For Galileo and Cassini, opnav uses image of the satellites in order to accurately target its flybys of those bodies, as well as help improve the overall ephemeris accuracies of the satellites.

Opnav is especially critical for missions to small bodies because their ground based ephemerides are only accurate to the tens to hundreds of km for asteroids, and up thousands for comets. The Galileo encounters of Gaspra and Ida, NEAR, Deep Space 1 (DS1), Stardust, and Deep Impact (DI) missions all could not have been possible without it. In addition to the flybys of these bodies, opnav is necessary for characterizing the shape, orientation, and spin rate of these bodies, which is critical for close approaches or landings. Optical images are also used for planetary Entry Descent, and Landing (EDL), such as the DIMES system used on the Mars Exploration Rovers for reducing the lateral velocity before impact. Future requirements to perform pinpoint landings on any of these targets drive the continuing need for cameras.

Historically, opnav has been performed using cameras whose primary purpose is as a science instrument. The trend however, is to develop a dedicated opnav camera which is affordable both in terms of cost, mass, and power. Such camera is being flown as a demo on MRO. This camera has a focal length of 500 mm, an aperture of 60 mm, uses 3-5 W of power, but weighs only 2.8 kg. With improvements in ground processing, the accuracy of this should rival that of Cassini's 25 kg camera. Further improvements in a dedicated camera would be to place it gimbals, which reduces or eliminates the need to slew the entire spacecraft in order to take images. Improvements in onboard image processing methods to compress large images and extract out relevant information without sending back the entire image also can improve the amount of opnav data sent back, thus contributing to improved navigation results. This kind of camera will make opnav possible as main or complementary navigation type for many missions, including small missions that need to navigate autonomously in the proximity of small bodies.

As a related but distinct topic, the DSN is also considering the use of optical frequencies for communications with deep space assets, and in that case there could also be the possibility of adding metric capabilities to the communication system in order to measure range very accurately. The big difference with respect to near-Earth laser ranging systems is that, due to the great distance, corner cube reflectors could not return enough signal, so a regenerative optical transponder would need to be used, with the difficulty of reliably calibrating transponder delays in order to be able to obtain high-precision measurements.

Re-engineer the Navigation Toolset

Most of the software tools that are currently being used operationally at JPL for navigation and mission design have evolved from tools that were first developed in the late 1960s and 1970s, so they still have the limitations associated with the FORTRAN/mainframe software development paradigm. At that time memory, disk space, processing resources, and bandwidth were scarce, so the software and the interfaces were optimized to be economical with all of those resources, at the expense of maintainability and usability. Nowadays we have in our laptops better performance in every measure than that of the best computers in the world thirty years ago. That is why we need to re-engineer the navigation and trajectory design software set in order to take advantage of rapidly evolving hardware capabilities, including parallel processing, and to enable further ground automation. The legacy software is difficult to maintain and extend, and cannot be easily adapted to take advantage of modern computing paradigms. We need to re-engineer the software to be able to use modern software engineering approaches that reduce extension and maintenance costs, and to enable high- and low-level parallelization using multiple processors.

DSMS is moving towards a modern Information Systems Architecture (ISA), based on three main tenets[4]: systems are composed of a loosely coupled collection of well-defined and interoperable network-accessible services and tools; information is defined externally to any given service or tool and is readily available to all authorized users; client interfaces and displays are decoupled from their underlying processing and data management functions. DSMS is also participating in the Consultative Committee for Space Data Systems[5] (CCSDS), working with other space agencies to develop recommendations and standards for space systems, in order to further interoperability in the international space community. As we re-engineer the navigation and mission design software, we will base it on the DSMS ISA infrastructure paradigm and use as much as possible standard interfaces defined by the CCSDS.

In addition we will need to add new modeling, processing, analysis, and optimization capabilities that can enable new types of deep-space missions, including low-thrust and low-energy trajectory design and control, tools for integrated optimization and control of closely coupled GNC systems, enhanced analysis capabilities for aero-assist and in-situ architectures, and multi-mission autonomous navigation tools.

Develop General-Purpose Autonomous Navigation Capabilities

Autonomous Navigation (Autonav) for spacecraft has two primary benefits; one is to enhance or enable missions which would otherwise not be possible due to round-trip light time or other limitations, the other is to potentially reduce costs by reducing the number of people needed for routine navigation operations. Autonav was first used on the DS1 mission as a technology experiment. DS1 used optical images of asteroids to perform orbit determination and then guide the spacecraft's trajectory by performing maneuvers, either with long term control of the ion engines or with impulsive delta-vs using hydrazine thrusters. Both were successfully demonstrated during the interplanetary cruise phase of the mission. A subset of this software was then used to control camera pointing during its flyby of the comet Borrelly; this same software was also used for the Stardust flyby of comet Wild 2. A heritage DS1 Autonav system was used by DI impactor to control its trajectory to a high enough accuracy to hit a lit side of Tempel 1, as well as image the resultant crater from the flyby spacecraft.

The above missions show examples of the mission enhancing capabilities of Autonav. For example, in all the comet flybys, most or all of the frames have the target in them as compared to a non-autonomous flyby, such as the Galileo Gaspra or Ida flybys, where dozens of images were taken in order to capture the target in a handful of frames. For the DI impactor, Autonav was enabling in that the comet had to be resolved in order to hit a lit spot on the nucleus; this only occurred several hours before impact which precluded ground control due to the light time. The DS1 cruise case illustrates an example where Autonav could reduce the number of ground navigators needed for a during a long and relatively quiescent cruise phase.

Up to now, Autonav use has been limited to small body flyby and impact missions. However, there are many new missions and mission phases of very high exploration and scientific value, such as ascent, pinpoint landing, deep-space or Mars-orbit rendezvous, and deep-space formation flying, that require more reliance on close-loop integrated six-degrees-of-freedom control of attitude and trajectory, and that cannot be performed with the ground in the loop. Thus, in order to fully realize the benefits of Autonav, the current DS1/DI heritage system needs to be re-engineered to make it more general and applicable to a wider range of missions. For example, the current system only uses optical data, whereas future missions will need additional data types such as LIDAR, or in situ radiometric data. The integration of new hardware with the software, such as the Inertial Stellar Compass, which can provide attitude determination as well as translational information if combined with Autonav, is also being pursued. The experimental MRO opnav camera is another piece of hardware which can be folded into an Autonav system; this camera combined with a gimbal could make it very attractive for lower-cost Discovery or Mars Scout missions to autonomously and safely operate in close proximity to a small body, or to land or navigate at Mars.

Improve Frequency and Timing Systems

Highly-stable frequency standards reduce the need for two-way data types and, because there is no need to close the communication link, free users from round-trip light time constraints. They also allow multiple users to be served by just one asset, decreasing the cost of supporting multiple spacecraft. Currently multiple Mars spacecraft can be tracked simultaneously using just one DSN antenna; but only one of them can be tracked in two-way mode. Only when the spacecraft tracked in one-way mode has an ultra-stable oscillator (USO), like Mars Global Surveyor (MGS) does, is the one-way data suitable for trajectory determination. In the future we could have in-situ GPS-like systems at the Moon or Mars, with a few high-orbit spacecraft serving many low-orbit and landed assets, and USOs would be needed at least for the service provider spacecraft, in order for the users to be able to obtain real-time trajectory and timing solutions. Furthermore, the user spacecraft should also have USOs in order to reduce the number of required service-provider spacecraft and to enable the use of sparse data with dynamics-based orbit determination approaches.

In addition, many parts of the Frequency and Timing Subsystem (FTS) of the DSN are obsolescent. The systematic upgrading of the FTS on an element-by-element basis, which has been underway for several years, should be continued.

Develop In-situ Tracking Infrastructure

NASA already has multiple assets at Mars providing – MGS, Odyssey – and using – Mars Exploration Rovers – in-situ communications and navigation capabilities. In-situ radio-metric tracking was used by the MER mission in order to improve the position determination of the landed rovers, and to allow for the imaging of the rovers by MGS. MRO is hosting a proximity radio that can be used by other future missions. Phoenix and Mars Science Laboratory are planning to use in-situ radio-metrics for EDL reconstruction and landed position determination. In the future we may have high-orbit dedicated relay spacecraft that provide longer tracking passes for landed or low-orbit assets, and that can track spacecraft arriving or departing Mars. We are developing radios and software that can exploit these in-situ capabilities, and can enable high-precision trajectory and position determination, even for real-time application, such as during guided EDL for pinpoint landing.

These kinds of capabilities may also be available at other bodies of interest, starting with the Moon in order to allow for global communications and navigation capabilities in support of Lunar exploration, and eventually at other solar system bodies such as Europa or Titan, in order to allow for simpler landed assets, more precise navigation, and increased data rates.

CONCLUSION

In the future NASA is going to develop and operate missions that require navigation capabilities that are beyond what is available today. DSMS has identified the main challenges for these future missions, and developed strategies to enable the successful operation of these missions. The capabilities enabled by these strategies will also be available to other NASA centers and applications, such as Human and Robotic Lunar Exploration, so they do not have to be developed from scratch, and can reduce schedule, risk and cost.

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